

# Quarkonium measurements via the di-muon decay channel in p+p and Au+Au collisions with the STAR experiment

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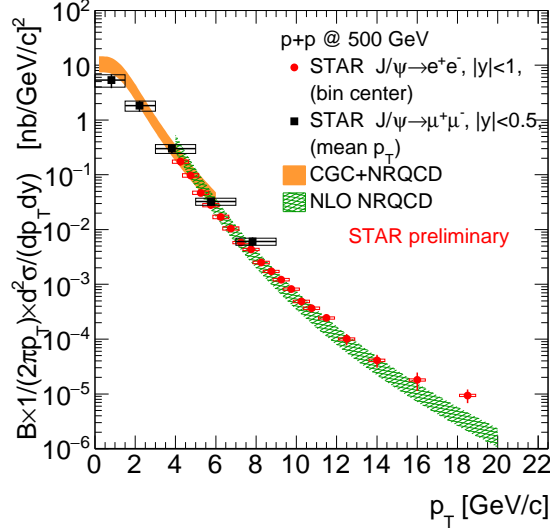
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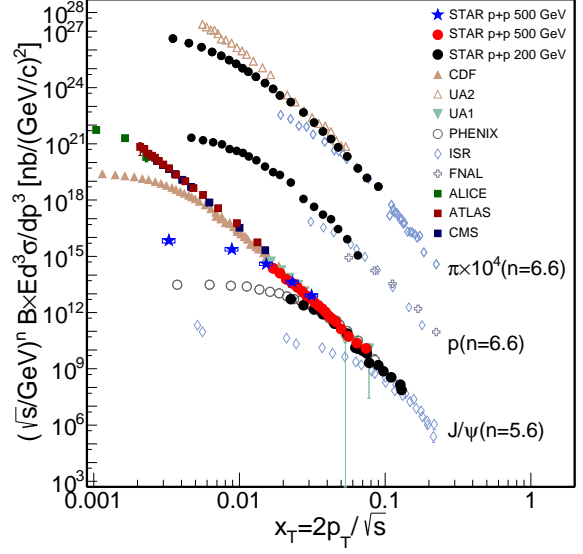
**Abstract.** We present the first  $J/\psi$  and  $\Upsilon$  measurements in the di-muon decay channel at mid-rapidity at RHIC using the newly installed Muon Telescope Detector. In p+p collisions at  $\sqrt{s} = 500$  GeV, inclusive  $J/\psi$  cross section can be described by CGC+NRQCD and NLO NRQCD model calculations for  $0 < p_T < 20$  GeV/c. In Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, we observe (i) clear  $J/\psi$  suppression indicating dissociation; (ii)  $J/\psi$   $R_{AA}$  can be qualitatively described by transport models including dissociation and regeneration with a tension at high  $p_T$ ; and (iii) hint of less melting of  $\Upsilon(2S + 3S)$  relative to  $\Upsilon(1S)$  at RHIC compared to that at LHC.

## 1. Introduction

Quarkonia are an essential probe to study the properties of the Quark Gluon Plasma (QGP). The suppression of  $J/\psi$  due to color-screening effects in the medium was initially proposed as a direct evidence of the QGP formation [1]. However, the interpretation of the  $J/\psi$  suppression is still a challenge due to the contributions from the regenerated  $J/\psi$  by the recombination of  $c\bar{c}$  pairs in the medium and the cold nuclear matter effects. Therefore it is important to have more precise  $J/\psi$  measurements over a broad kinematic range and even cleaner  $\Upsilon$  state measurements. The latter do not suffer from the regeneration contribution due to the much smaller  $b\bar{b}$  pair cross section, i.e.  $\sigma_{b\bar{b}} \sim 2 \mu\text{b}$  [2] while  $\sigma_{c\bar{c}} \sim 800 \mu\text{b}$  [3] at top RHIC energy. The newly installed Muon Telescope Detector (MTD), which provides both the di-muon trigger and the muon identification capability at mid-rapidity, opens the door to measuring quarkonia via the di-muon decay channel at STAR. Compared to the di-electron decay channel, the di-muon decay channel suffers much less from bremsstrahlung and thus provides much better invariant mass resolution to separate different  $\Upsilon$  states. Using the MTD di-muon trigger, the STAR experiment recorded data corresponding to an integrated luminosity of  $28.3 \text{ pb}^{-1}$  in p+p collisions at  $\sqrt{s} = 500$  GeV in the RHIC 2013 run, and  $14.2 \text{ nb}^{-1}$  in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV in the RHIC 2014 run. In these proceedings, we report (1) the measurements of  $J/\psi$  production in p+p collisions at  $\sqrt{s} = 500$  GeV; and (2) the measurements of the nuclear modification factor ( $R_{AA}$ ) for  $J/\psi$  and the production of different  $\Upsilon$  states in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV.



**Figure 1.**  $J/\psi$  cross section scaled by the branching ratio  $B$  as a function of  $p_T$  in the di-muon decay channel (black circle) and in the di-electron decay channel (red circle).



**Figure 2.**  $x_T$  scaling of  $J/\psi$  cross section scaled by the branching ratio  $B$  in the di-muon decay channel (blue star) and in the di-electron decay channel (red circle).

## 2. $J/\psi$ measurements in p+p collisions at $\sqrt{s} = 500$ GeV

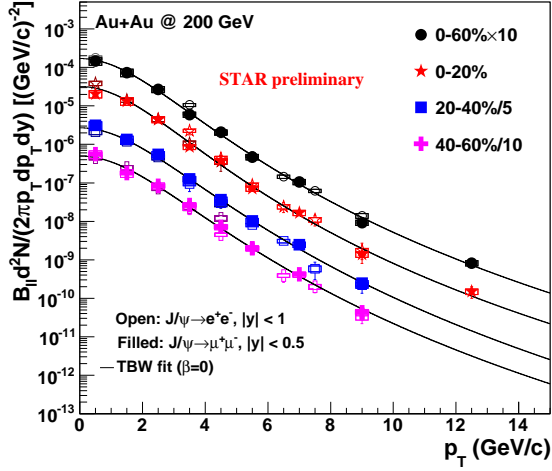
Figure 1 shows the cross section of  $J/\psi$  in p+p collisions at  $\sqrt{s} = 500$  GeV in the di-electron and di-muon decay channels for  $0 < p_T < 20$  GeV/c. The di-muon decay channel extends  $p_T$  reach down to 0 GeV/c. The results in these decay channels are consistent in the overlapping  $p_T$  range of  $4 < p_T < 9$  GeV/c. The experimental results can be well described by CGC+NRQCD calculations at low  $p_T$  [4] and NLO NRQCD calculations at high  $p_T$  [5]. Figure 2 shows the  $x_T = 2p_T/\sqrt{s}$  scaling of  $J/\psi$  cross section [6]. The  $J/\psi$  cross section in p+p collisions at  $\sqrt{s} = 500$  GeV follows the common trend as a function of  $x_T$  at high  $p_T$ . The breaking of the  $x_T$  scaling at low  $p_T$  can be attributed to the soft processes.

## 3. $J/\psi$ measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

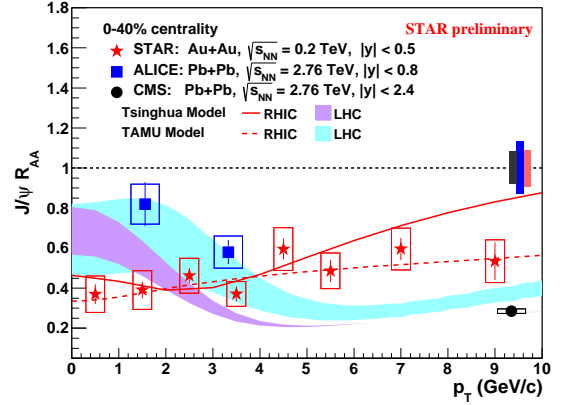
Figure 3 shows the invariant yield of  $J/\psi$  in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV for different collision centralities. The new results in the di-muon decay channel are consistent with previous results in the di-electron decay channel [7, 8] within uncertainties.

The nuclear modification factor  $R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dy dp_T}{d^2 \sigma_{pp}/dy dp_T}$  of  $J/\psi$  in 0-40% central Au+Au collisions is shown in Fig. 4, compared with LHC results [13, 14]. The strong suppression at RHIC at low  $p_T$  indicates that dissociation plays a significant role in this  $p_T$  range. The hint of the increasing trend of  $R_{AA}$  at RHIC at high  $p_T$  can be explained by formation-time effects and feed-down of  $B$  hadrons. The less suppression of  $J/\psi$  at LHC at low  $p_T$  indicates larger regeneration contribution due to higher charm cross section, while more suppression of  $J/\psi$  at LHC at high  $p_T$  indicates larger dissociation rate due to higher temperature of the medium. Transport Models from Tsinghua [9, 10] and Texas A&M University (TAMU) [11, 12], including dissociation and regeneration effects, can qualitatively describe the  $p_T$  dependence of RHIC and LHC data.

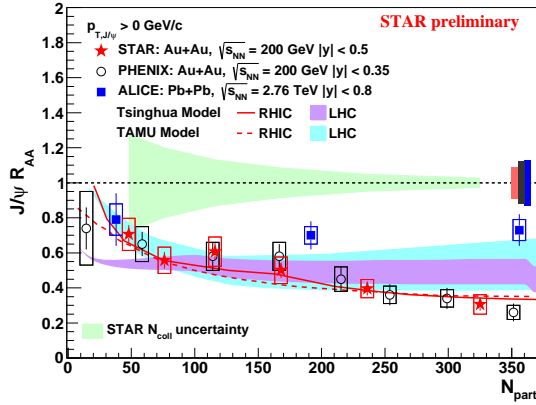
Centrality dependence of  $J/\psi$  cross section is shown in Fig. 5 for integrated  $p_T$  and in Fig. 6 for  $p_T > 5$  GeV/c. For integrated  $p_T$ , both models can describe centrality dependence at RHIC, but tend to overestimate suppression at LHC. For  $p_T > 5$  GeV/c, there is tension among models



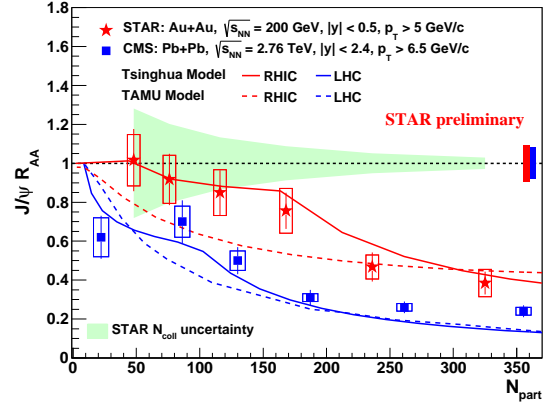
**Figure 3.** Invariant yield of  $J/\psi$  scaled by the branching ratio  $B_l$  as a function of  $p_T$  in different centralities in the di-muon decay channel (filled) and in the di-electron decay channel (open) .



**Figure 4.**  $R_{AA}$  as a function of  $p_T$  at RHIC (red star) and at LHC (blue square, black circle). The lines and bands indicate Transport Model calculations for RHIC and LHC energies.



**Figure 5.** Nuclear modification factor  $R_{AA}$  for integrated  $p_T$  as a function of  $N_{part}$ .

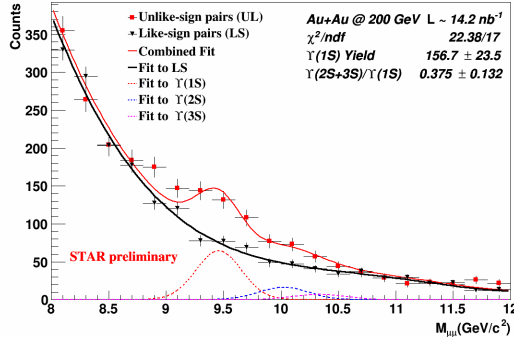


**Figure 6.** Nuclear modification factor  $R_{AA}$  for  $p_T > 5$  GeV/c as a function of  $N_{part}$ .

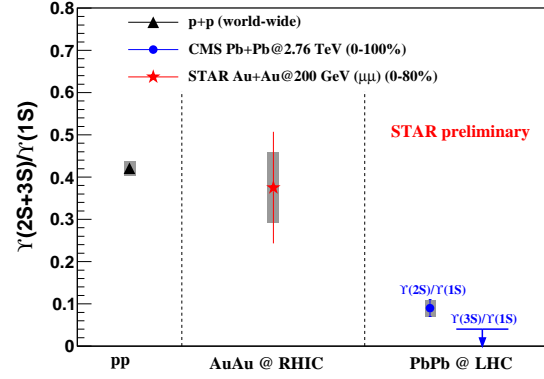
and data. New measurements in the di-muon decay channel provide a distinguishing power for these transport models.

#### 4. $\Upsilon$ measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Figure 7 shows the di-muon mass spectrum in  $\Upsilon$  state mass range in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. We observe signs of an indication of  $\Upsilon(2S + 3S)$  signals in the di-muon decay channel. The raw yields of  $\Upsilon$  states are obtained by a simultaneous fit to the like-sign and unlike-sign distributions. In this fit, (i) the  $\Upsilon$  state masses are fixed to the PDG values and their widths are determined by simulation; (ii) the ratio of  $\Upsilon(2S)/\Upsilon(3S)$  is fixed to the value in p+p collisions; and (iii) the shape of  $b\bar{b}$  and Drell-Yan background is estimated using PYTHIA. Figure 8 shows the fitted  $\Upsilon(2S + 3S)/\Upsilon(1S)$  ratio compared with the world-wide p+p data [16] and CMS data [17, 18]. There is a hint of less melting of  $\Upsilon(2S + 3S)$  relative to  $\Upsilon(1S)$  at RHIC



**Figure 7.** Di-muon mass spectrum in the  $\Upsilon$  state mass range.



**Figure 8.**  $\Upsilon(2S+3S)/\Upsilon(1S)$  ratio for world-wide p+p data, and for heavy-ion collisions at RHIC, and LHC energies.

than at LHC.

## 5. Summary and Outlook

We present the first  $J/\psi$  and  $\Upsilon$  measurements in the di-muon decay channel at mid-rapidity at RHIC. In p+p collisions at  $\sqrt{s} = 500$  GeV, inclusive  $J/\psi$  cross section can be described by CGC+NRQCD and NLO NRQCD model calculations for  $0 < p_T < 20$  GeV/c. In Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, we observe (i) clear  $J/\psi$  suppression indicating dissociation; (ii)  $J/\psi$   $R_{AA}$  can be qualitatively described by transport models including dissociation and regeneration despite a tension at high  $p_T$ ; and (iii) there is a hint of less melting of  $\Upsilon(2S + 3S)$  relative to  $\Upsilon(1S)$  at RHIC compared to that at LHC. These measurements in Au+Au collisions will have better statistical precision by combining the similar amount of data recorded in the RHIC 2016 run.

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